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CLYDE TUNNEL REFURBISHMENT: MODELLING THE PERFORMANCE OF THE NEW LINING SYSTEM AND DRAINAGE CHANNEL IN THE EVENT OF A FIRE.

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Abstract

The Clyde Tunnel in Glasgow, Scotland, is currently undergoing refurbishment. This refurbishment includes the installation of a new tunnel lining / fire protection system in both tunnel tubes. This lining system has already been shown to protect the tunnel structure from high temperatures However, there is a gap at the lower edge of the lining to allow any water accumulated behind the lining to run into a drainage channel within the main tunnel void. There were concerns that this small gap might lead to the exposure of the structural members to very high temperatures in the event of a fire in the tunnel.

A heat transfer analysis was carried out. This analysis consisted of the evaluation of the thermal field inside the tunnel using Computational Fluid Dynamics (CFD) computations. This identified the locations in the tunnel which were most likely to be at risk, and predicted the conditions at those locations in the event of a 'worst case' fire scenario. On the basis of this information a bounding heat transfer analysis was carried out that allowed the establishment of the temperature evolution of the structural elements. CFD tools were not used for the heat transfer analysis because the complexity of the geometry made the uncertainty too large to justify a detailed CFD study. Instead, this bounding analysis allowed the establishment of the maximum possible temperatures of the structural elements.

It was found that, even in a 'worst case' scenario fire, the temperature of the structural elements would not exceed critical levels for several hours of maximum fire exposure. The design of the lining / channel is held to be more than satisfactory in this case.

Introduction

(a) The Clyde Tunnel

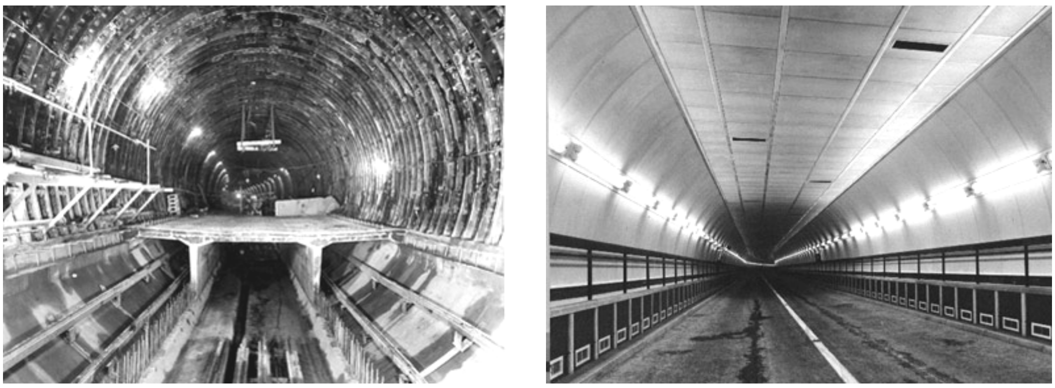

Figure 1 – Photographs of the tunnel during construction and the original tunnel lining.

The construction of the second[†] road tunnel under the river Clyde was started in 1957 and the northbound tube was opened by Queen Elizabeth II in 1963. The southbound tube opened the following year. The tunnels are 762m long, are constructed out of iron sections and, when they

[†] The first tunnel under the Clyde, the 'Harbour Tunnel', was built in the 1890s. It was accessed by hydraulic lifts in the two 'rotundas' (which can still be seen on the banks of the Clyde). The tunnel was closed to vehicles in 1943 and the lifts were removed. It was closed to pedestrians in 1986 and filled-in in 1987.

opened, were the steepest road tunnels in the world with a 6% slope (1:16). In 1957, the expected traffic density was 9,000 vehicles per day; in 1965 22,000 vehicles used the tunnel on a daily basis; today the daily traffic flow is over 65,000 vehicles. The original ventilation system was fully transverse, with air supplied through vents along the kerbside and periodic extraction vents along the ceiling, see Figure 1.

(b) The refurbishment

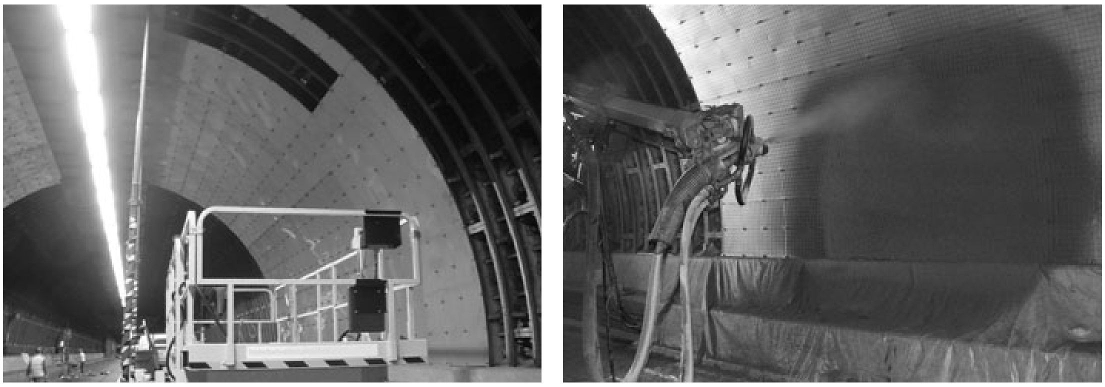

Figure 2 – Photographs of the tunnel during refurbishment and the application of the fire protection.

The £9M refurbishment of the Clyde Tunnel includes the installation of a new tunnel lining / fire protection system in both tunnel tubes, an overhaul of the ventilation system and the installation of a state of the art video monitoring system.

The primary requirement of the new lining system is that it should protect the iron sections of the tunnel structure in the event of a fire. The lining system consists of a steel framework attached to the iron sections, this is covered by steel sheeting and a wire mesh, to which a 40mm layer of cementitious fire protection is applied, by spraying in-situ, see Figure 2. This lining system has been furnace tested in the laboratory and has been shown to adequately protect the structural members from temperatures up to 1350°C for over two hours, according to the standard time-temperature curve proposed by Rijkwaterstaat, the Netherlands (hereafter referred to as the RWS curve) [1].

(c) The problem

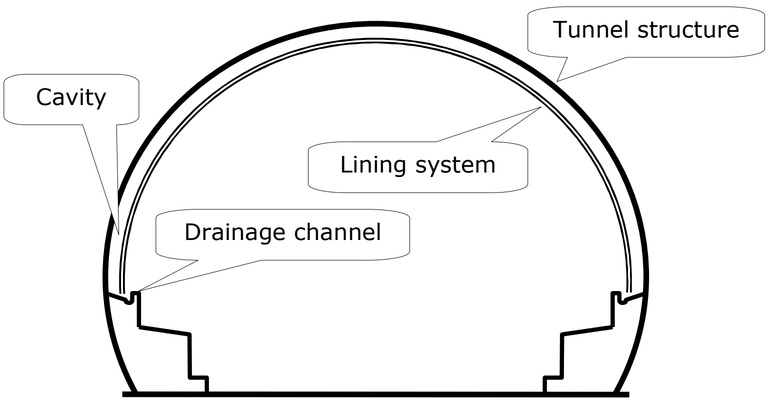

Figure 3 – Simplified representation of the tunnel cross-section showing the lining system and the drainage channel.

One of the secondary functions of the lining system is to act as a drip shield, such that all leakage into the tunnel runs down the outer side of the lining system and drains into a channel in the main tunnel void[‡]. In order to allow the water to pass from the cavity into the tunnel void, there has to be a gap between the lower edge of the lining system and the concrete which forms the drainage channel and protects the lower parts of the tunnel structure, see Figure 3. There was some concern that this gap might allow the structural members of the tunnel to be exposed to high temperatures in the event of a fire in the tunnel.

The University of Edinburgh were contracted to analyse the problem and report on the safety of this design. The analysis of the problem was carried out in two stages:

- Various scenarios involving a fire in the tunnel were simulated using a computer fire model, to determine the conditions in the vicinity of the gap in the event of a fire, and
- The heat transfer to the tunnel structure was calculated, based on the 'worst case' values obtained from the computer simulations.

Methodology

Due to the design of the gap and the drainage channel, there is no direct line-of-sight path for heat transfer from the void into the cavity by radiation, so it is assumed that any heat transfer into the cavity will be due to a pressure driven flow of hot gas. Thus the objective of the computer simulations was to identify those parts of the tunnel, near the gap, which exhibited the highest pressures. The rate of gas flow into the cavity could then be estimated if the pressure in the cavity is assumed to remain at ambient; this is deemed to be an extreme 'worst case' assumption as, in reality, the pressure would most likely be above ambient initially and would increase to be equal to the void pressure (thus eliminating the flow) within a matter of moments.

It was also assumed that the gas flow into the cavity would only transfer heat to the iron sections of the tunnel and not to the back of the lining material; this is another 'worst case' assumption. In reality there would be heat losses to the rear of the lining material and thus there would be less heat transfer to the structural elements.

Computer simulations

The conditions in the tunnel in the event of a fire were modelled using the 'Fire Dynamics Simulator' (FDS) model (version 4). FDS is a computational fluid dynamics (CFD) model, developed by the National Institute of Standards and Technology (NIST) in the USA [2]. This code is of generalized use in the Fire safety Engineering community and relevant validation exercises can be found in the literature supplied by the developers.

As the requirements of the lining system are those of the RWS fire, the aim of the modelling was to simulate fires in the tunnel which would generate peak gas temperatures of about 1350°C and then predict the peak temperatures and pressures in the vicinity of the gap. The growth and decay phases of the fires were not of direct relevance to the study, so the simulations carried out considered high heat release rate (HRR) fires with a constant output, so that the simulations would approximate to 'steady-state' conditions. This scenario is actually more severe than the RWS fire as the standard fire only remains at a peak temperature for a limited time.

All computer models have limitations and in the case of FDS they pertain mostly to the combustion model and radiation heat transfer associated to fire growth. As this study did not require the prediction of the fire burning behaviour (the fires were prescribed) or radiation, most of the limitations of FDS could be ignored.

[‡] Throughout this paper the word 'cavity' will be used to describe the space between the lining system and the tunnel structure, whereas the word 'void' will be used to describe the main vehicle space in the tunnel.

However, the requirement that the simulated environment be constructed out of rectilinear cells cannot be overlooked. The upper parts of the Clyde Tunnel cross-section have a semi-circular aspect which must be represented by rectangular blocks in the simulated tunnel. This is not a particularly significant problem in this instance as the steps do not have a severe influence in the global nature of the flow. Temperatures, pressures and flow velocities depend mostly on the global behaviour of the flow, thus the 'step-like' geometry will provide very similar results to a smoothly curved wall. Also, the parts of the tunnel which are of interest are reasonably 'step-like' in themselves.

The cross-sectional profile of the simulated environment is shown in Figure 4. The geometry of the tunnel has been simplified to being constructed out of $1m^3$ cubes, thus the kerb, elevated walkway and drainage channel have all been represented by a 1m high by 1m wide block at the side of the roadway. At eight locations through the tunnel, the fire safety installations have been included, modelled as a 1m high, 1m wide (as viewed in cross-section) and 2m deep box. The gas temperature and pressure have been recorded at various locations in the tunnel at the apex of the ceiling, beside the gap and just above each of the fire safety boxes.

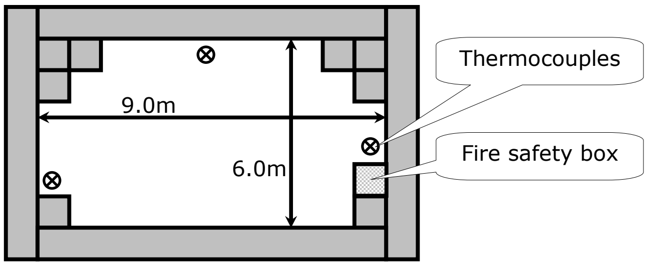

Figure 4 – Typical cross-sectional profile of the simulated tunnel (with safety box)

The longitudinal profile of the simulated tunnel was based on the plans of the east tube, which has a slope of approximately 1:17 on the northern side and a slope of approximately 1:16 on the southern side. The simulated tunnel was therefore constructed out of long, 1m high steps, each 17m long on the north side and 16m long on the south side. The lowest section of the tunnel (between the first step on each side) was 33m long. There were twenty steps on each side. The longitudinal profile of the model tunnel is shown in Figure 5. The computational domain extended above and beyond the ends of the tunnel to allow modelling of the plume away from the portals.

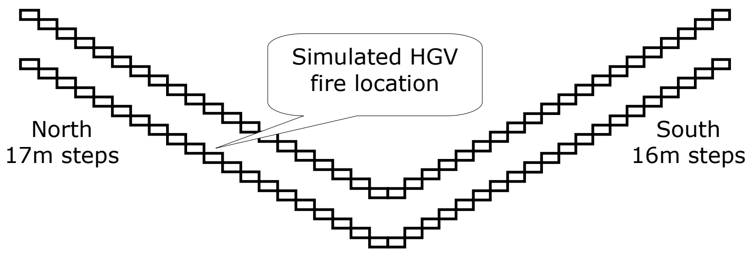

Figure 5 – The longitudinal profile of the model tunnel (not to scale)

Modelling results

If there was a large fuel spillage in the tunnel, for example a fuel tanker shed its load, the fuel would flow to the lowest point of the tunnel and form a pool. If this was to catch fire, a serious incident would develop. The first simulations carried out involved large fuel pools at the lowest point in the tunnel. The initial run was carried out prescribing a fuel vaporisation rate equivalent to a HRR of 220MW and assuming natural ventilation conditions. In this instance the HRR calculated by the model was substantially lower than the prescribed value as there was insufficient oxygen to allow burning at this level. As a consequence of this, the peak temperatures in the tunnel were only of the order of

600°C and nowhere near the required level. Several subsequent runs were attempted, varying the prescribed HRR and the ventilation, but none of these scenarios attained the peak temperatures required due to the (lack of) oxygen supply at the lowest point in the tunnel.

Further simulations were attempted using the scenario of a HGV fire about halfway up the slope on the north side of the tunnel. In this scenario, it was expected that all the smoke, hot gases and combustion products would flow up the tunnel to the north, due to buoyancy effects, while fresh air would be drawn in from the south in sufficient quantities to elevate the HRR of the fire and the temperatures in the tunnel to the values required by the RWS curve. The HGV was modelled as being on the 9th step up on the north side. Various HRR values were prescribed over the course of several simulations, and the predicted ceiling temperatures only satisfied the RWS curve requirements when the HRR was set at 500MW or higher.

It should be noted that heat release rates of the order of 500MW are highly unrealistic for fires in tunnels. The highest measured HRR for an experimental fire in a tunnel was just over 200MW. This was for a mock up of a HGV trailer in a nearly horizontal tunnel, loaded with nearly 11 tonnes of wooden and plastic pallets, subject to a forced longitudinal airflow [3]. Even multiple vehicle fires in tunnels have not been estimated to have exhibited HRRs of this scale. In the Channel Tunnel fire of November 1996, the fire involved ten HGVs and their carrier wagons, and the peak HRR of that fire has been estimated to have been about 350MW [4]. Very high temperatures, as simulated by the RWS curve, are only expected to be produced during fires in tunnels which are close to horizontal. In tunnels with significant gradients, such as the Clyde Tunnel, the smoke and hot gases produced by a fire will be transported away much more rapidly, due to buoyancy effects. This will tend to lead to smaller temperatures in the tunnel. In the event of a fire in the Clyde Tunnel, it is highly unlikely that the temperatures in the tunnel would be as high as those simulated by the RWS curve. Thus is has been necessary to use an unrealistically high prescribed HRR to simulate the temperature conditions required by the RWS standard. Therefore, the modelled scenario has to be considered as an “extreme worst case” condition.

The results of the 500MW HGV fire simulation are presented in the figures that follow. Figure 6 shows representations of the temperature, velocity and pressure profiles on the centreline of the tunnel at ‘steady state’ condition.

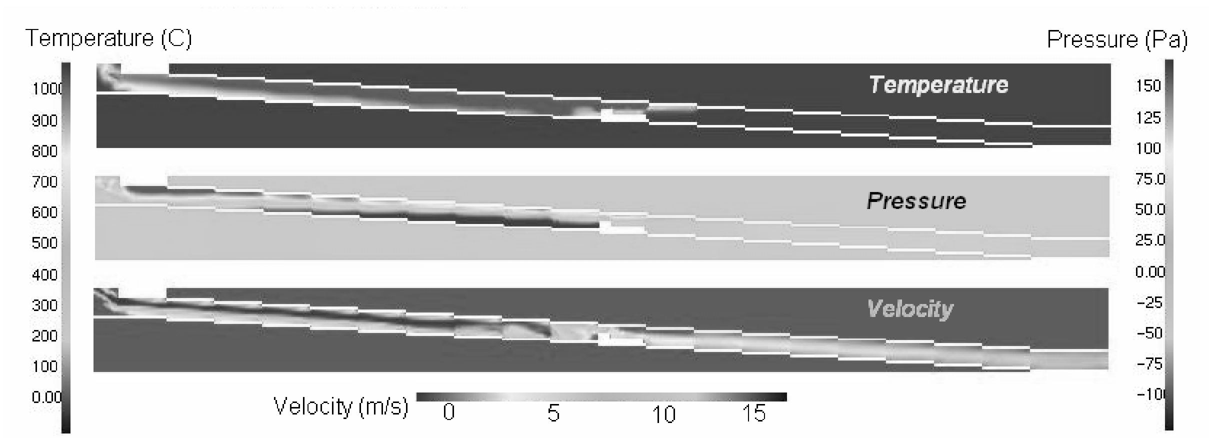

Figure 6 – ‘Steady state’ conditions for a 500MW HGV fire on the north slope of the Clyde Tunnel, eastern tube.

The steady state temperature and pressure recorded at the virtual thermocouples at the ceiling and the gap are shown in Figures 7-10. In each graph, the data are presented versus distance along the tunnel; measured in 17m ‘steps’ from the HGV location (184-196m from the portal) towards the north portal.

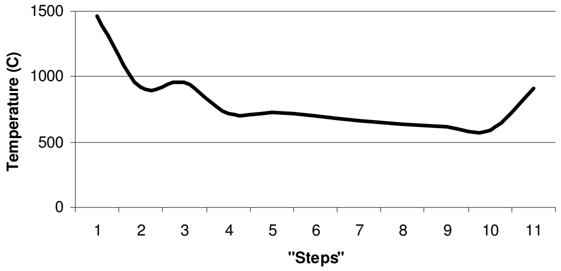

Figure 7 – ‘Steady state’ ceiling temperature versus distance along the tunnel.

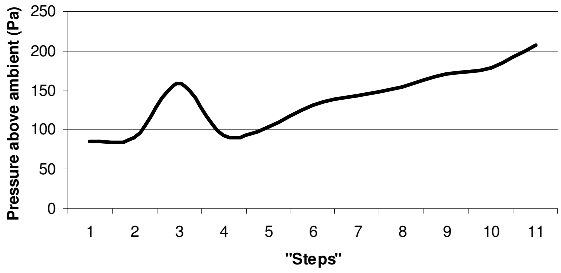

Figure 8 – ‘Steady state’ ceiling pressure versus distance along the tunnel.

(‘Step 1’ is the location of the HGV and ‘step 11’ is close to the portal; each ‘step’ is 17m long.)

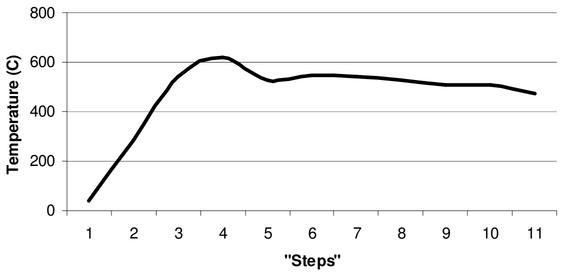

Figure 9 – ‘Steady state’ temperature at the gap.

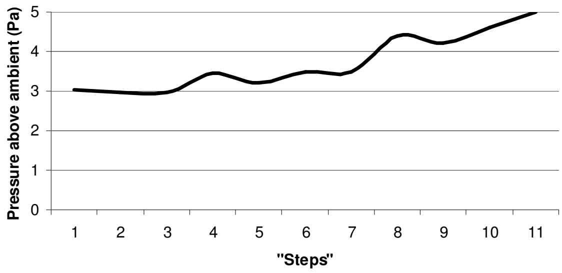

Figure 10 – Average ‘steady state’ pressure at the gap .

It is clear from Figure 10 that the pressure conditions near the gap were generally found to be at approximately ambient pressure, that is, at most gap locations there would be no pressure-driven flow of hot gas into the cavity in the event of a fire, as the pressure difference between the cavity and the void would be insignificant.

The only significant variation from this trend is above the safety box in the first fire point recess (nearest the portal), where the pressure reached a value of about 50 Pa above ambient pressure, see Figure 11. Thus it is necessary to calculate what the effect of the flow of hot gas (at about 510°C, see Figure 12) into the cavity at this point would be.

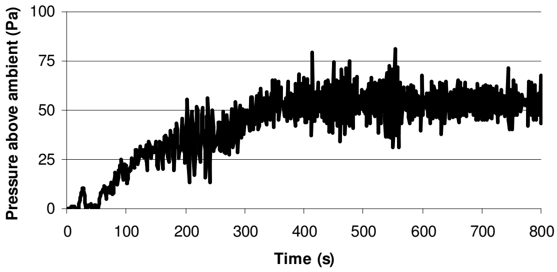

Figure 11 – The pressure profile recorded above the first safety box.

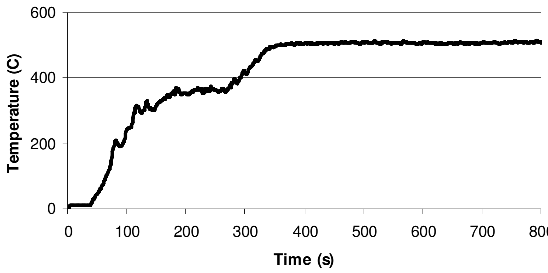

Figure 12 – The temperature profile recorded above the first safety box.

Flow of hot gas into the cavity

Calculations have been made for the case of a flow of hot gas (assumed to be hot air) at 510°C into the cavity, which is assumed to remain at ambient pressure. In reality, the pressure in the cavity would most likely be much closer to the pressure in the tunnel void, so the flow would be expected to be smaller. Also, due to the volume and geometry of the cavity, it is likely that a pressure balance would be reached fairly quickly and so the flow would cease early in the fire development. Thus, these calculations are to be taken to represent a 'worst case' scenario; in reality the flow, and hence the heat transfer to the tunnel structure would be much less significant than calculated here.

Based on the temperature and pressure calculated in the tunnel, the gas density is taken to be:

$$\rho = \frac{P}{RT}$$

where R is the universal gas constant, taken to be 287.05 $Jkg^{-1}K^{-1}$.

Thus, $\rho = \frac{100050}{287.05 \times 783} = 0.445$ kgm^{-3} in the vicinity of the gap above the 1st safety box.

From Bernoulli's theorem, the velocity of a fluid passing through an opening can be taken to be:

$$V = C_d \sqrt{\frac{2 \times \Delta P}{\rho}}$$

where C_d is the "coefficient of discharge" which generally has a value of about 0.6 for instances like this where there is a pressurised flow through an orifice [5], thus:

$$V = 0.6 \sqrt{\frac{2 \times 50}{0.445}} = 8.99 \text{ ms}^{-1}.$$

In the scenario considered, the gas jet passes through a narrow gap into the void behind the panel which is taken to be about 0.3m wide for the most part. Thus the velocity will be reduced according to the ratio of the width of the opening to the width of the gap behind the panel. Thus, if the gap is 50mm wide, the velocity will reduce by $^{50}/_{300}$ in the void to give 1.5ms^{-1}, or if the gap is 30mm wide, the velocity will reduce by $^{30}/_{300}$ in the void to give 0.9ms^{-1}, and so on. Thus there is a flow of hot gas at about 510°C flowing over the iron segments of the tunnel with a velocity of up to 1.5ms^{-1} (depending on the geometry of the gap). In the analysis presented here we will assume the gap is 50mm wide, hence the velocity over the tunnel structure is taken to be 1.5ms^{-1}.

Convective heat transfer rates are governed by a number of non-dimensional groups. In order to calculate the heat transfer to the iron sections, it is necessary to calculate the Nusselt number of the flow. The Nusselt number (Nu) is a function of the Reynolds number (Re) and the Prandtl number (Pr) which define the relationship between the inertia and viscosity of a fluid and the relationship between the momentum diffusivity and thermal diffusivity of a fluid, respectively. These may be found using the following equations:

$$\text{Re} = \frac{\rho V L}{\mu} \quad \text{and} \quad \text{Pr} = \frac{\nu}{\alpha} = \frac{\mu c_p}{k}$$

where L is a characteristic length scale, μ is the dynamic viscosity, α is the thermal diffusivity, υ is the kinematic viscosity, c_p is the specific heat at constant pressure and k is the thermal conductivity.

Assuming the width of the cavity behind the lining (i.e. 0.3m) to be the characteristic length, the Reynolds number (taking the viscosity of air at 500°C from [5]) is:

$$\text{Re} = \frac{0.445 \times 1.5 \times 0.3}{3.64 \times 10^{-5}} = 5501$$

and the Prandtl number may be found, directly from a table in a text book [5], to be Pr = 0.7 for air at approximately 500°C. If the flow over the iron panel is laminar, the local Nusselt number may be found using:

$$\mathrm{Nu} = 0.664 \times \mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} = 0.664 \times 74.2 \times 0.888 = 43.75$$

Whereas if the flow is fully turbulent, the local Nusselt number may be found using:

$$\mathrm{Nu} = 0.0296 \times \mathrm{Re}^{4/5}\,\mathrm{Pr}^{1/3} = 0.0296 \times 982.5 \times 0.888 = 25.82$$

The convective heat transfer coefficient, *h*, can be calculated from the Nusselt number:

$$\mathrm{Nu} = \frac{hL}{k} \qquad \Rightarrow \qquad h = \frac{\mathrm{Nu} \times k}{L} = \frac{25.82 \times 55 \times 10^{-3}}{0.3} = 4.7$$

taking the value of *k* for air at 500°C from [5] and assuming turbulent flow. Having established *h* as being about 4.7 $\mathrm{Wm^{-2}K^{-1}}$, we need to calculate temperature rise in the iron. For a solid of unit surface area we have:

$$Vc_p\rho\frac{dT}{dt} = h\left(T_\infty - T_s\right)$$

where *V* is volume (= 1 × 1 × 0.03), not velocity. c_p and ρ values for iron can be found in a text book (= 447 and 7870, respectively, from [5]). If we define the temperature difference between the gas and the solid as:

$$\theta = T_s - T_\infty$$

The problem resolves to:

$$\frac{d\theta}{dt} + m\theta = 0 \text{ where } m = \frac{h}{Vc_p\rho} = \frac{4.7}{0.03 \times 447 \times 7870} = 4.45 \times 10^{-5} \text{ (approx. constant)}$$

This has the solution:

$$\theta = \theta_0 e^{-mt} = -500 \times e^{-4.45 \times 10^{-5}\,t}$$

For example, after two hours of exposure to the heated flow, the temperature rise of the iron is:

$$\theta = \theta_0 e^{-mt} = -500 \times e^{-4.45 \times 10^{-5} \times 7200} = -363°$$

Thus, after two hours, the temperature of the iron is 363° below the hot gas temperature, i.e. 147°C.

The calculated temperature rise of the iron with time is shown in Figure 13.

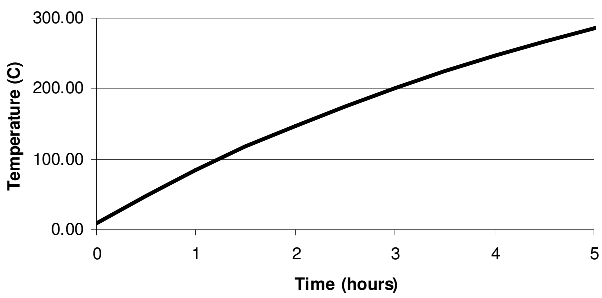

Figure 13 – Calculated temperature rise of unit area of tunnel structural section with time.

It should be noted that the results calculated here and displayed in Figure 13 take no account of heat losses from the structural members of the tunnel, either to the gas flow or to the surrounding ground. If these losses were taken into account, the rate of temperature rise would be slower.

Conclusions

A numerical study of a fire within the Clyde Tunnel has been conducted. The heat release rate of the fire was defined so that the temperatures within the tunnel reached the values described by the RWS standard. This study was complemented by heat transfer calculations to establish the impact of a lower gap on the temperatures of the structural members behind the protective lining. The following conclusions can be drawn:

- To obtain the RWS curve the HRR used has to be established at values which are unrealistically high. Given the geometry of the tunnel, ventilation will limit the temperatures within the tunnel to values well below the RWS curve. This results in a conservative analysis.
- The pressure distributions within the tunnel show that pressures close to the gaps are generally at or below ambient, thus hot gases will generally not enter through the gap.
- Specific regions where there is a potential for above ambient pressure near the gap were identified. Local peak pressures and temperatures were identified and used to calculate the flow of hot gases through the gap. An idealized heat transfer analysis, that includes no losses, was conducted. The analysis showed that after 2 hours of fire exposure the temperature of the structural elements will reach only 147°C. This analysis can be deemed as very conservative.
- Given the nature of the imposed fire and the uncertainty of the conditions within the tunnel, a simple but very robust and conservative approach was preferred. A more detailed analysis of the flow and heat transfer within the gap could not be justified given the definition of this problem.

Acknowledgements

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